HERITAGE COMPUTING REPORT

PEER REVIEW OF THE GASCOYNE RIVER FLOODPLAIN AQUIFER MODEL

FOR

WESTERN AUSTRALIA DEPARTMENT OF WATER

By

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1.0 INTRODUCTION

This report provides a peer review of the numerical groundwater model for the Lower Gascoyne region of Western Australia, situated upstream of Carnarvon about 900 km north of Perth. A groundwater flow and solute transport model has been developed by Cymod Systems Pty Ltd for the Department of Water, Western Australia (DoW).

Substantial use is made of groundwater for public water supply and the local horticulture industry. DoW is reviewing the allocation plan for the management of surface and groundwater resources in this region and requires the assistance of a modelling tool to assess alternative resource management strategies.

The review has been conducted at the conclusion of the draft reporting phase of the modelling project. The reviewer has not participated in earlier stages of the project, and has had no direct contact with Cymod Systems.

2.0 MODELLING GUIDELINES

The review has been structured according to the checklists in the Australian Flow Modelling Guideline (MDBC, 2001). This guide, sponsored by the Murray-Darling Basin Commission, has become a *de facto* Australian standard. This reviewer was one of the three authors of the guide, and is the person responsible for creating the peer review checklists. The checklists have been well received nationally, and have been adopted for use in the United Kingdom, California and Germany.

The modelling has been assessed according to the 2-page Model Appraisal checklist in MDBC (2001). This checklist has questions on (1) The Report; (2) Data Analysis; (3) Conceptualisation; (4) Model Design; (5) Calibration; (6) Verification; (7) Prediction; (8) Sensitivity Analysis; and (9) Uncertainty Analysis.

The effort put into a modelling study is often dependent on timing and budgetary constraints that are generally not known to a reviewer.

3.0 EVIDENTIARY BASIS

The primary documentation on which this review is based is:

1. *Cymod Systems Pty Ltd, 2010, The Development of the Gascoyne River Floodplain Aquifers Modelling System: GASFAMS V1.1. November 2010 [3 volumes].*

No other documentation has been referenced in doing this review.

4.0 PEER REVIEW

In terms of the modelling guidelines, the GASFAMS model is categorised as an *Aquifer Simulator* of high complexity as distinct from an *Impact Assessment Model* of medium complexity.

The Australian best practice guide (MDBC, 2001) describes the connection between model application and model complexity as follows:

- Impact Assessment model - a moderate complexity model, requiring more data and a better understanding of the groundwater system dynamics, and suitable for predicting the impacts of proposed developments or management policies; and
- Aquifer Simulator - a high complexity model, suitable for predicting responses to arbitrary changes in hydrological conditions, and for developing sustainable resource management policies for aquifer systems under stress.

An Aquifer Simulator model is the appropriate level of complexity, as the model is to be used for water allocation decisions.

The appraisal checklists are presented in Tables 1 and 2 (at the back of this report). The current review has been based entirely on a written report, with no reference to electronic model files.

5.0 DISCUSSION

5.1 THE REPORT

The Report (Document #1) is a substantial, high quality document of 87 pages for Volume 1, 89 pages for Volume 2, and seven Appendices in Volume 3. To an external reader with no prior knowledge of the study area, the report is very good as a standalone document without need of supporting documents.

The objectives of the modelling study and the scope of work to address those objectives are articulated clearly in Section 2 (Modelling Objectives). The specific objectives are stated as:

- *"Simulate groundwater flow within and between all hydrogeological units in the Gascoyne River floodplain groundwater system.*
- *Establish water budgets for each aquifer.*

- *Under a range of scenarios, including pumping and climate variations, predict the scale of changes in recharge, groundwater potentiometric heads/water levels and groundwater salinity within the hydrogeologic units.*
- *Evaluate likely changes in groundwater discharge to ocean environments.*
- *Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.*
- *Provide results that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).*
- *Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses."*

The report concludes with an assessment of whether the individual objectives have been satisfied. This is rarely done and is to be commended.

This reviewer agrees with the author as to the degree to which the objectives have been met. The findings and the recommendations are well substantiated.

There is ample coverage of the modelling component of the study, with full disclosure of model parameterisation.

Task (d) in the approach for meeting the objectives, namely "calibrating and verifying the numerical model to December 2007", requires updating as the calibration extended to December 1999 and verification to 2008.

5.2 DATA ANALYSIS

There are substantial sections on Environmental Setting (Section 3), Geology (Section 4) and Hydrogeology (Section 5). The study has benefitted from considerable prior investigations including a number of pumping tests that have informed the characterisation of the transmissive and storage natures of the aquifer system.

There is a substantial record of groundwater level variations (hydrographs) at 257 bores, and water quality data for 227 bores. To inform conceptualisation, it would have been informative to display representative hydrographs that show clear cause-and-effect relationships between groundwater variables (water level, salinity) and stresses (rainfall, river stage, pumping) and proximity to the coast.

The units in column 5 of Table 22 should be GL/a instead of kL/a.

5.3 CONCEPTUALISATION

The conceptualisation of the local hydrogeology is defensible and is discussed in detail, in terms of geology and key recharge/discharge processes.

Very good graphics are provided in support of the conceptualisation by means of longitudinal and transverse conceptual sections for flow and solute (Figures 8-11). The solute diagrams could have indicated the qualitative salinity of the various water sources.

There are issues related to aquifer continuity and effective basement. While they are addressed in detail, they remain uncertainties that propagate through to model predictions. To allow for continuity of sandy lenses over the planned spatial resolution of the model (~100 m), a pragmatic representation of the stratigraphy has been made by incorporating a series of multiple layers of notional thicknesses. Given the complex heterogeneity of the natural system, there is really no other way to do this.

A decision has been made to regard the Toolonga Formation as effectively impermeable. This formation is described as a "fine-grained carbonate" and has a single field measurement of 4 m/day, which seems high for such a formation. If its permeability is this high, it could contribute water and salt from below and from upgradient where it outcrops. For allocation purposes, the model predictions can be regarded as conservative in their assessment of volumetric sustainability of the resource.

5.4 MODEL DESIGN

The flow model has been built with MODFLOW-2000 within the Visual MODFLOW Graphic User Interface (GUI). The solute model uses MT3DMS.

Given the occurrence of dry cells, the use of MODFLOW-SURFACT would better handle desaturated conditions caused by pumping. It would also be better for the solute modelling, but the Visual MODFLOW GUI disables the ACT ("And Contaminant Transport") part of SurfACT. The latter couples the flow and transport algorithms at the time step level, whereas MT3DMS links at the stress period level.[1]

It appears that SURFACT was the initial choice for modelling, but there were issues in linking with MIKE11 and ACT, and instability was associated with the use of pseudo-soil functions. The latter can be obviated in SURFACT by use of van Genuchten parameters, and convergence is almost guaranteed with use of the ATO time discretisation package. It is not clear

[1] The author notes with regret that Visual MODFLOW is a poor choice as the standard for DoW – this reviewer wholeheartedly agrees.

why "the use of MODFLOW Surfact excluded using MIKE11 to simulate one-dimensional surface water flow". In principle, MIKE11 could have generated the river stages required by the RIV or STR packages in MODFLOW.

Discretisation in space is appropriate. Model cells are a minimum 50 m x 83 m in Area A, increasing to a maximum 250 m x 2000 m elsewhere. There are 200 columns and 151 rows. The model has 10 layers. There does not appear to be a calculation of the Peclet Number as a guide to likely stability of the solute transport simulation. Stability improves as grid size decreases.

The narrow north-south dimension does not have a clearly defined width. The northern boundary has been settled as the distance at which there is no discernible variation in groundwater levels due to river dynamics. This is a sensible algorithm as long as river recharge dominates other recharge mechanisms.

The coastal boundary has been modelled correctly with a no-flow boundary at depth (Layers 4-10) and fixed heads in the upper layers. This has the effect of forcing groundwater upwards from the deep layers, as would happen in nature at the salinity interface, and be available for discharge through ET or coastal outflow mechanisms. No explanation is offered for the use of 0.865 mAHD as the constant head value, other than reference to an earlier model. It should certainly exceed zero, as saline groundwater requires density correction in MODFLOW, which assumes equivalent freshwater heads. Strictly speaking, the boundary head values should increase with depth due to the increasing thickness of salty water, and this will further encourage the upwards migration of groundwater near the coast.

The broad model extent isolates the boundaries from likely impacts and reduces the need for accurate representation of boundary fluxes which are set as no-flow for most boundary cells except for prescribed heads at the upstream boundary. Final predicted drawdowns verify that the adopted boundary conditions have had no undue effect.

It has been remarked already in Section 5.3 that the Toolonga Formation might not be impermeable and that it could contribute water and salt through the upgradient boundary.

Multi-node wells (MNW) have been used to represent groundwater pumping across the Older Alluvium Aquifer (OAA), down to Layer 4, as the notional stratigraphy does not permit attribution of pumping to distinct layers. This is a sensible approach, but (if not done already) the modelled and recorded volumes should be checked for approximate equivalence. It is noted that a different GUI (Groundwater Vistas) had to be used to generate the MNW input file.

Calculation of a minimum time step size is commendable, and is very rarely seen in modelling reports. The applied formula, however, is for an explicit solution. Implicit solutions (which are the standard) are much more generous, usually by a factor of 100. The reviewer uses the following (unpublished) formula for estimation of the maximum permissible time step after a stress event:

$$DELT(1) \quad \leq \quad \frac{25\,S\,L^2}{T}$$

where S is the minimum specific yield, L is the minimum cell width, and T is the maximum transmissivity.

The use of non-uniform stress periods is a good idea for tracking river events.

While latitude in initial heads is tolerable, initial concentrations can control a solution, presumably due to the discrepancy between nature’s time scales and those in a model. It is extremely difficult to define a reliable set of initial concentrations. For this reason, a solute model might have some value in the simulation of salinity differentials with time, or in scenario analysis, but would rarely be reliable in tracking absolute salinity magnitudes.

Simulation of dynamic flood extent has been done cleverly. Essentially, the maximum extent is declared as RIV cells. Whether a RIV cell provides flood recharge or not will depend on the interpolated river stage (in a potentially flooded cell) relative to the notional river bed level in that cell. However, the reviewer has a concern that a negative flux might be calculated when the cell is not flooded (i.e. hRIV < RBOT) unless the cell conductance (COND) is set to zero. How has this been accomplished?

Rainfall recharge is said to occur in those months when the river does not flow and rainfall exceeds 38 mm. The reviewer is concerned that peripheral rainfall recharge might be ignored on the floodplain when the river is flowing. This should be clarified. The report then states that rainfall recharge “has been set to zero in the GASFAMS model”, due to its relatively minor contribution. This seems to be an extreme choice as it denies some contribution to yield and to freshening of water quality. A calculation of the likely volume of water foregone from the budget should be reported to demonstrate that it is insignificant. The solute transport model does recognise the capacity of rainfall infiltration to contribute salt to the system. This is introduced to the model as a distributed mass loading of 0.001 $g/m^2/day$ (for TDS of 10 mg/L). This rate should be justified; it appears to imply an infiltration rate of 15%.

For evapotranspiration, there is no statement on the adopted ETmax rate. This should be substantially less than the potential ET (reported in Section 3) due to MODFLOW’s linear approximation, and should be guided by the “actual ET” estimate on the BoM website.

5.5 CALIBRATION

Calibration has been performed for transient conditions, for flow and salinity. Several lines of evidence are provided in support of calibration in the form of a scatter plot, performance statistics, individual hydrograph matches, and residual maps. Overall, the transient flow calibration is quite good, with satisfactory performance statistics: 5 % average absolute error and 2.2 m absolute RMS.

In general, the replication of hydrographic trends is good. Amplitude is mostly overestimated but some hydrograph matches are quite good. Nearly always, the response is too rapid. This feature of a natural system is controlled by the storage (S, Sy) parameters and by stress propagation. The parameter distributions in Appendix F show little if any spatial variability in the storage values. Use of PEST software should improve the calibration.

It is noted that the calibration data set is deficient spatially in not having any bores at distance from the river. Hence, this part of the aquifer system is not well known.

The solute calibration appears to be reasonably good, but this agreement might be illusory as it is very much determined by the choice of initial salinities. Some time series plots show good agreement; others show inconsistent trends and poor amplitude matching.

5.6 VERIFICATION

Hydrographic verification has been performed from 2000 to 2008. Without a residual mass graph (or other climate trend indicator), it is not immediately clear whether this period of time had significantly different climatic conditions from the calibration period.

The verification process appears to have performed better than calibration, according to the statistical performance indicators: 4 % average absolute error and 0.9 m absolute RMS. This gives some confidence in the predictive power of the flow model.

The solute model verification appears to be marginally worse. Again, this is controlled by initial conditions.

5.7 PREDICTION

Predictions are based on transient simulation for either 8.6 or 10 years of pumping according to DoW-specified scenarios. There are three historical stress sequences; three stochastic sequences (of 20 years); and 13 abstraction scenarios.

Water balances for each scenario are reported in substantial detail for various spatial zones.

Ten model observation bores are used to display differential water levels and salinities for the various scenarios.

Borefield pumping seems to encourage freshening of the groundwater rather than a deterioration in water quality. Is this intuitively and conceptually correct?

5.8 SENSITIVITY ANALYSIS

A sufficient sensitivity analysis has been reported. This has been done by getting MODFLOW 2000 to report composite sensitivities, rather than the more common perturbation approach. Either approach is acceptable.

However, the adopted approach does not give an indication of how "tight" a parameter value is, in the sense of its effect on performance statistics. It does, however, identify the relative significance of the various model parameters.

5.9 UNCERTAINTY ANALYSIS

Uncertainty analysis is accomplished through scenario analysis for varying recharge. Sensitivity simulations in predictive mode provide a way of quantifying the uncertainty in predicted outcomes.

Borefield yields are expressed as useful probability graphs.

It is recognised that the major source of uncertainty in salinity predictions is due to the adopted initial distributions.

6.0 CONCLUSION

The Gascoyne groundwater flow model has been developed competently and is regarded as "fit for purpose" for use as a quantitative tool for determining borefield yields.

The solute model also has been developed competently, but the dependence of salinity predictions on assumed initial conditions does not allow much confidence in this aspect of the modelling. This is not a criticism of the modeller, but of the state of the art for salinity modelling. Improvement in the modelling cannot be expected unless a more comprehensive salinity distribution is measured, ideally via vertical profiles in a number of bores.

There are issues related to aquifer continuity and effective basement. While they are addressed in detail, they remain uncertainties that propagate through to model predictions.

This reviewer agrees with the author as to the degree to which the objectives have been met. The findings and the recommendations are well substantiated.

7.0 REFERENCES

Cymod Systems Pty Ltd, 2010, The Development of the Gascoyne River Floodplain Aquifers Modelling System: GASFAMS V1.1. November 2010 [3 volumes].

MDBC (2001). Groundwater flow modelling guideline. Murray-Darling Basin Commission. URL: http://www.mdbc.gov.au/nrm/groundwater/groundwater_guides/

Table 1. MODEL APPRAISAL: Gascoyne Model

Q.	QUESTION	Not Applicable or Unknown	RATING				COMMENT
1.0	THE REPORT						
1.1	Is there a clear statement of project objectives in the modelling report?		Missing	Deficient	Adequate	**Very Good**	Objectives and tasks in Section 2
1.2	Is the level of model complexity clear or acknowledged?		Missing	No	**Yes**		Aquifer Simulator Model, high complexity – MDBC guidelines acknowledged.
1.3	Is a water or mass balance reported?		Missing	Deficient	Adequate	**Very Good**	
1.4	Has the modelling study satisfied project objectives?		Missing	Deficient	Adequate	**Very Good**	Subject to stated limitations.
1.5	Are the model results of any practical use?			No	Maybe	**Yes**	
2.0	DATA ANALYSIS						
2.1	Has hydrogeology data been collected and analysed?		Missing	Deficient	Adequate	**Very Good**	
2.2	Are groundwater contours or flow directions presented?		Missing	Deficient	Adequate	**Very Good**	
2.3	Have all potential recharge data been collected and analysed? (rainfall, streamflow, irrigation, floods, etc.)		Missing	Deficient	Adequate	**Very Good**	
2.4	Have all potential discharge data been collected and analysed? (abstraction, evapotranspiration, drainage, springflow, etc.)		Missing	Deficient	**Adequate**	Very Good	What is ETmax?
2.5	Have the recharge and discharge datasets been analysed for their groundwater response?		**Missing**	Deficient	Adequate	Very Good	Correlation of groundwater hydrographs with stresses (rainfall, river stage, pumping) should be demonstrated. Residual mass rainfall analysis is useful for showing climate trends.
2.6	Are groundwater hydrographs used for calibration?			No	Maybe	**Yes**	Flow: 164 bores selected from 1447. Salinity: 150 bores selected from 227 (or 218?). More than sufficient.
2.7	Have consistent data units and standard geometrical datums been used?			No	**Yes**		Crosses two UTM zones. Table 22 kL/a → GL/a (column 5)
3.0	CONCEPTUALISATION						
3.1	Is the conceptual model consistent with project objectives and the required model complexity?		Unknown	No	Maybe	**Yes**	

3.2	Is there a clear description of the conceptual model?		Missing	Deficient	Adequate	Very Good	
3.3	Is there a graphical representation of the modeller's conceptualisation?		Missing	Deficient	Adequate	Very Good	Figures 8 & 9 – longitudinal & transverse flow sections. Figures 10 & 11 – longitudinal & transverse salinity sections.
3.4	Is the conceptual model unnecessarily simple or unnecessarily complex?			Yes	No		Pragmatic stratigraphic division. Multiple alternating layers – uncertain continuity.
4.0	MODEL DESIGN						
4.1	Is the spatial extent of the model appropriate?			No	Maybe	Yes	Thorough defence in all directions. 200 columns x 151 rows. 50-2000m cell sizes.
4.2	Are the applied boundary conditions plausible and unrestrictive?		Missing	Deficient	Adequate	Very Good	Generally no-flow at distant borders, and fixed heads at eastern and western limits. Sensible coastal boundary (no flow at depth) but 0.865 mAHD should be justified. MNW used for dynamic well pumping.
4.3	Is the software appropriate for the objectives of the study?			No	Maybe	Yes	Visual Modflow & Modflow 2000 & MT3DMS. MODFLOW-SURFACT would be better with many dry cells but ACT not linked to VM. Good idea: use of variable stress periods for RIV events, max 1 month.

Table 2. MODEL APPRAISAL: Gascoyne Model

Q.	QUESTION	Not Applicable or Unknown	RATING				COMMENT
5.0	CALIBRATION						May 1991 to December 1999
5.1	Is there sufficient evidence provided for model calibration?		Missing	Deficient	Adequate	Very Good	Several lines of evidence: scattergrams; performance statistics for transient (average absolute error (m, mg/L and %) and absolute RMS); residual at each bore; residual maps. Did not use PEST.
5.2	Is the model sufficiently calibrated against spatial observations?		Missing	Deficient	Adequate	Very Good	No bores away from the valley.
5.3	Is the model sufficiently calibrated against temporal observations?		Missing	Deficient	Adequate	Very Good	Trends are good. Amplitude mostly on the high side; some are quite good. Nearly always, the response is too rapid (S parameter controls this, and RIV stress propagation).
5.4	Are calibrated parameter distributions and ranges plausible?		Missing	No	Maybe	Yes	
5.5	Does the calibration statistic satisfy agreed performance criteria?		Missing	Deficient	Adequate	Very Good	5.1% average absolute error and 2.2mRMS; maximum residual 16m. Meets the MDBC guideline.
5.6	Are there good reasons for not meeting agreed performance criteria?		Missing	Deficient	Adequate	Very Good	Geological complexity.
6.0	VERIFICATION						2000-2008
6.1	Is there sufficient evidence provided for model verification?		Missing	Deficient	Adequate	Very Good	Several lines of evidence: scattergrams; performance statistics for transient (average absolute error (m, mg/L and %) and absolute RMS); residual maps.
6.2	Does the reserved dataset include stresses consistent with the prediction scenarios?		Unknown	No	Maybe	Yes	
6.3	Are there good reasons for an unsatisfactory verification?		Missing	Deficient	Adequate	Very Good	4.0% average absolute error and 0.9mRMS; maximum residual 7m. Meets the MDBC guideline.
7.0	PREDICTION						
7.1	Have multiple scenarios been run for climate variability?		Missing	Deficient	Adequate	Very Good	3 historical sequences. 3 stochastic sequences.

7.2	Have multiple scenarios been run for operational /management alternatives?		Missing	Deficient	Adequate	Very Good	13 abstraction scenarios. Infill bores introduced for high extraction rates.
7.3	Is the time horizon for prediction comparable with the length of the calibration / verification period?		Missing	No	Maybe	Yes	8.6 and 10 years prediction based on 18 years calibration & verification.
7.4	Are the model predictions plausible?			No	Maybe	Yes	
8.0	SENSITIVITY ANALYSIS						
8.1	Is the sensitivity analysis sufficiently intensive for key parameters?		Missing	Deficient	Adequate	Very Good	Use of MF2000 composite sensitivities rather than perturbation approach.
8.2	Are sensitivity results used to qualify the reliability of model calibration?		Missing	Deficient	Adequate	Very Good	
8.3	Are sensitivity results used to qualify the accuracy of model prediction?		Missing	Deficient	Adequate	Very Good	
9.0	UNCERTAINTY ANALYSIS						
9.1	If required by the project brief, is uncertainty quantified in any way?		Missing	No	Maybe	Yes	Thorough scenario analysis for varying recharge (not aquifer properties)